Predictive Adaptive Optics Control for High-Contrast Identification of Space Vehicles and Debris

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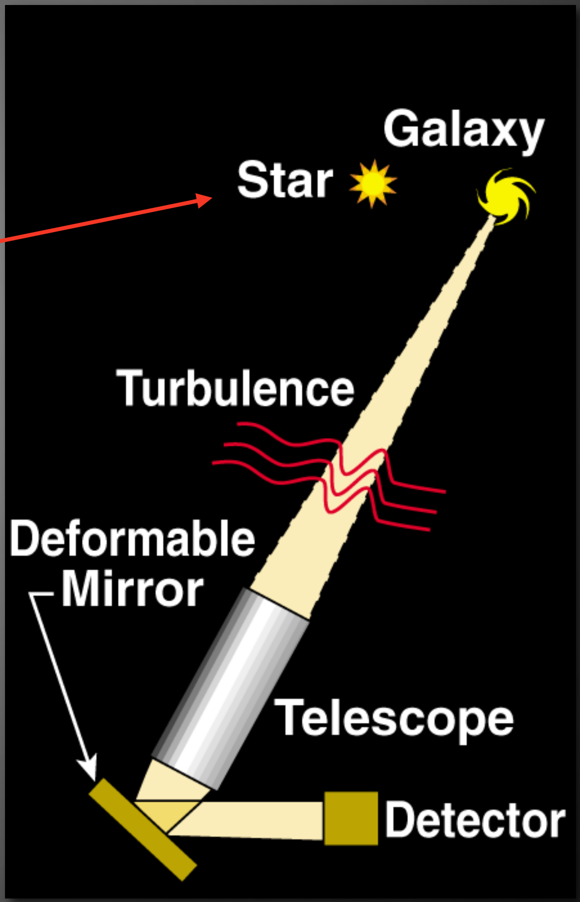
Outline

1. What is Adaptive Optics?
2. A Tomographic Approach to the Fast-Slewing Problem
3. Simulated Performance

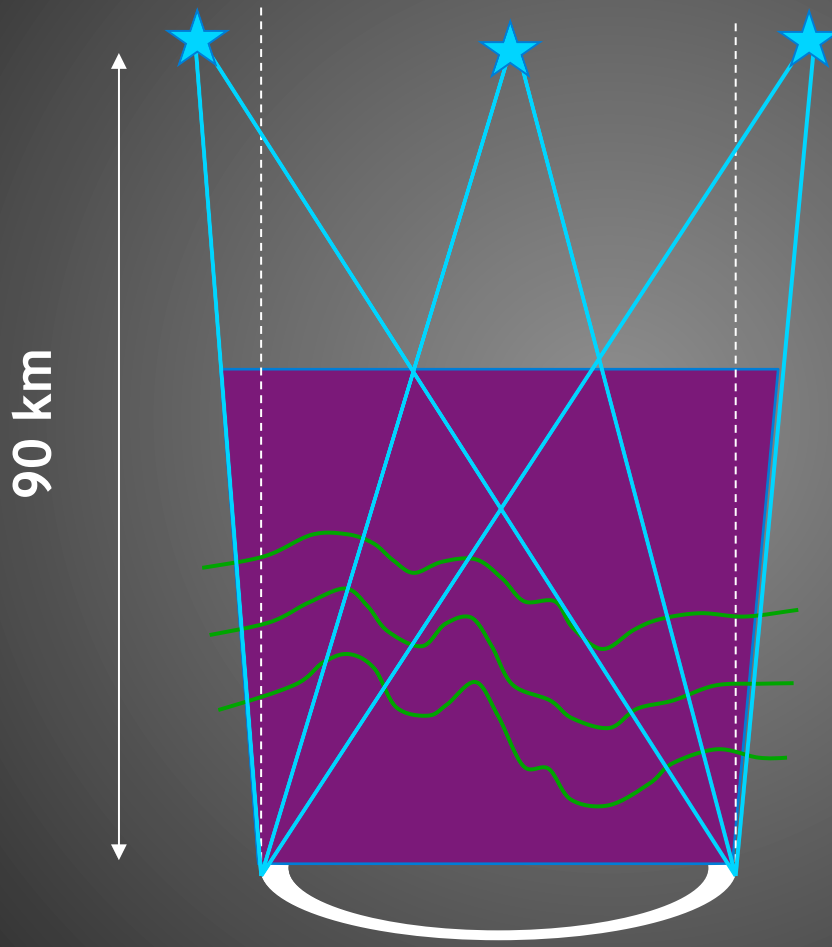
Laser Guide Star Adaptive Optics

Use a laser beam to create artificial “star” at altitude of 100 km in atmosphere



Credit: C. Max

What is Adaptive Optics Tomography ?



Tomography lets you reconstruct turbulence in the entire cylinder of air above the telescope mirror

Tomography is limited by the *finite number of sampling angles*, or limited size of guide star constellation.

Credit: Rigaut, MCAO for Dummies

Fast-Tracking Scenarios: Active Orbit Modification, Passive Satellite Identification

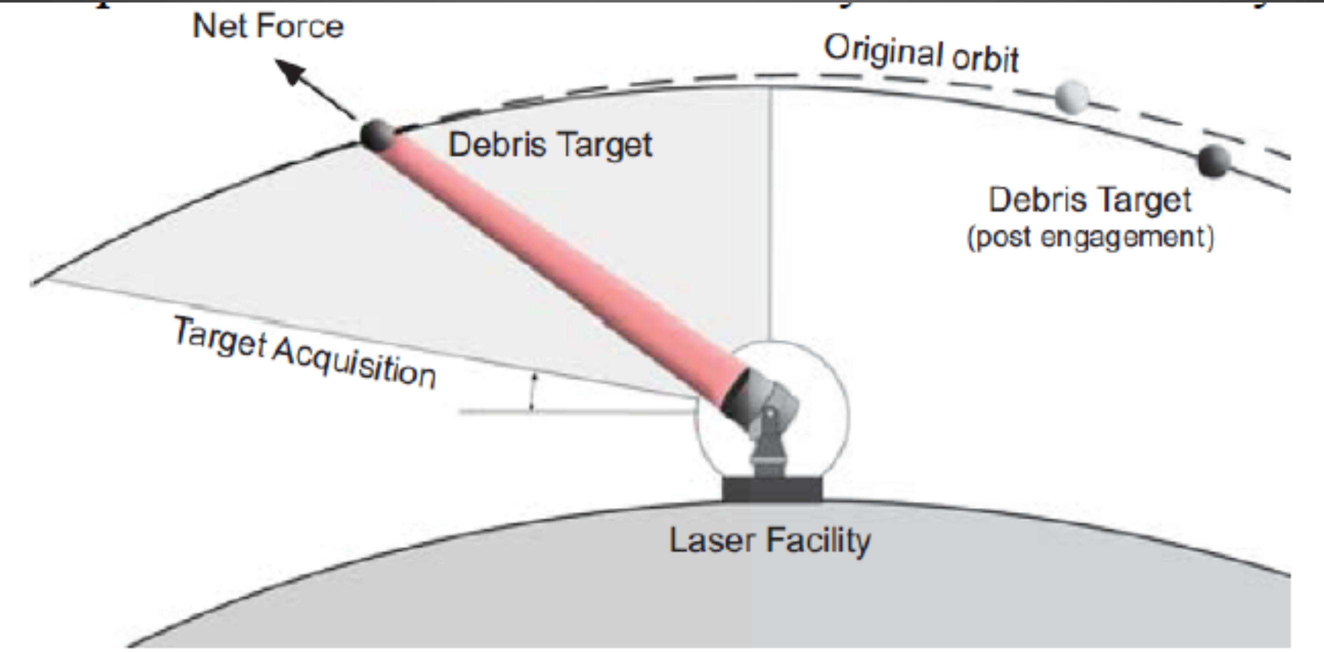
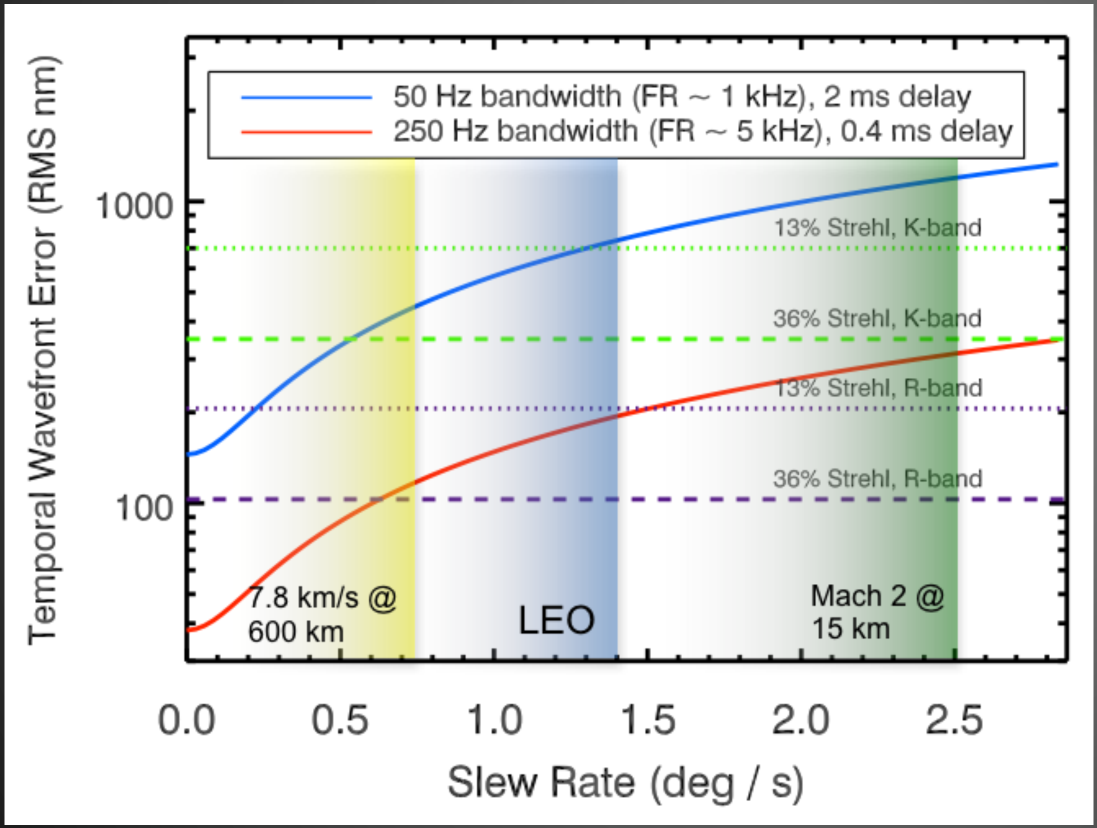


Fig. I: Schematic of laser system for orbital debris collision avoidance.

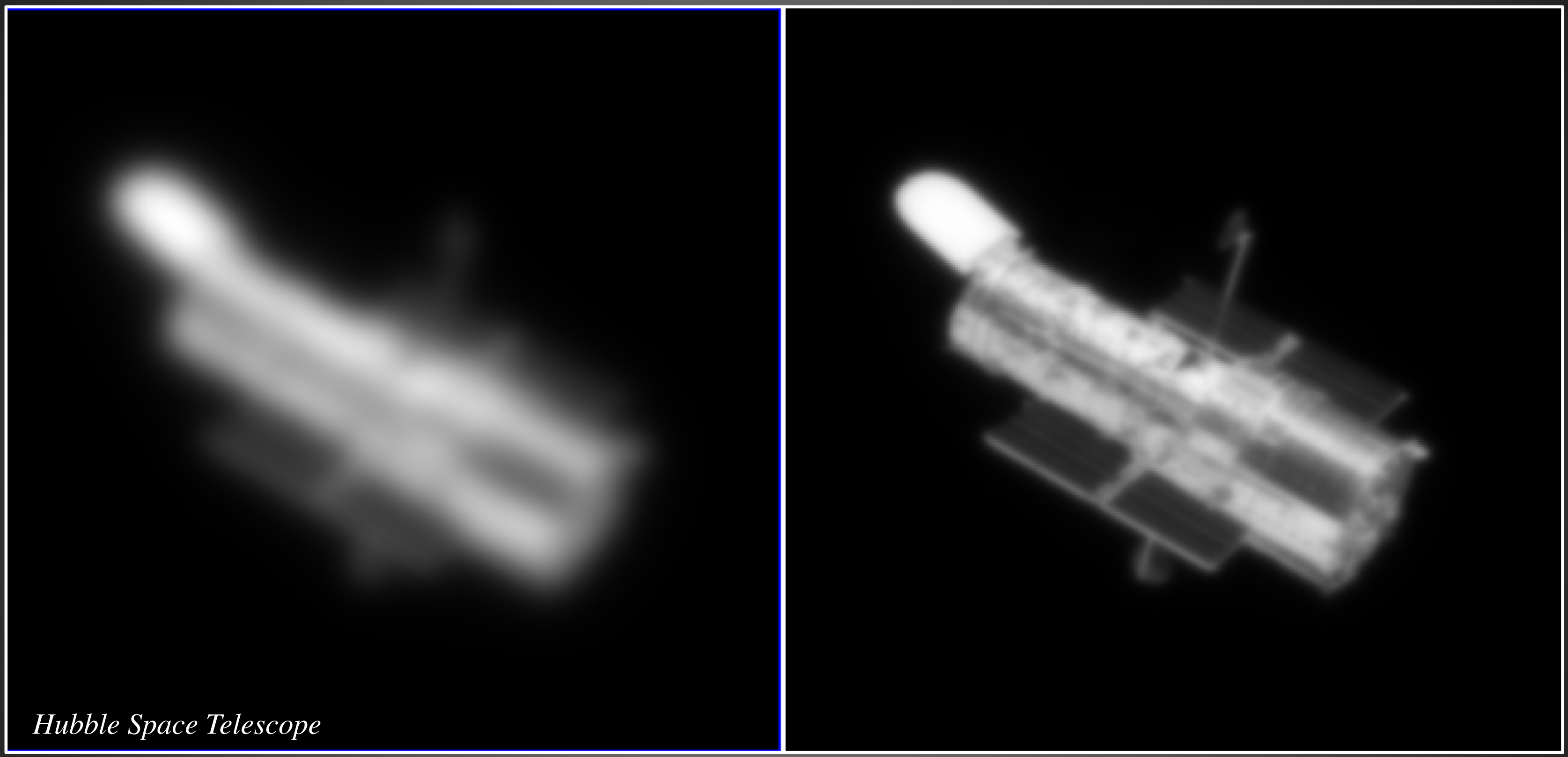
LightForce: Active Collision Avoidance using photon pressure induced by ground-based lasers. AO is needed to pre-correct laser beams for atmospheric turbulence (Stupl et al. 2011)

Temporal Errors are Large and Problematic in Fast-Slewing Telescopes



- In fast-tracking AO systems, temporal errors alone preclude diffraction-limited operation at optical/infrared wavelengths for tracking objects in LEO.
- Predictive schemes can reduce temporal errors, making high-strehl and high contrast imaging possible at fast slewing speeds.

Removal of Temporal Errors Necessary for Reliable Identification



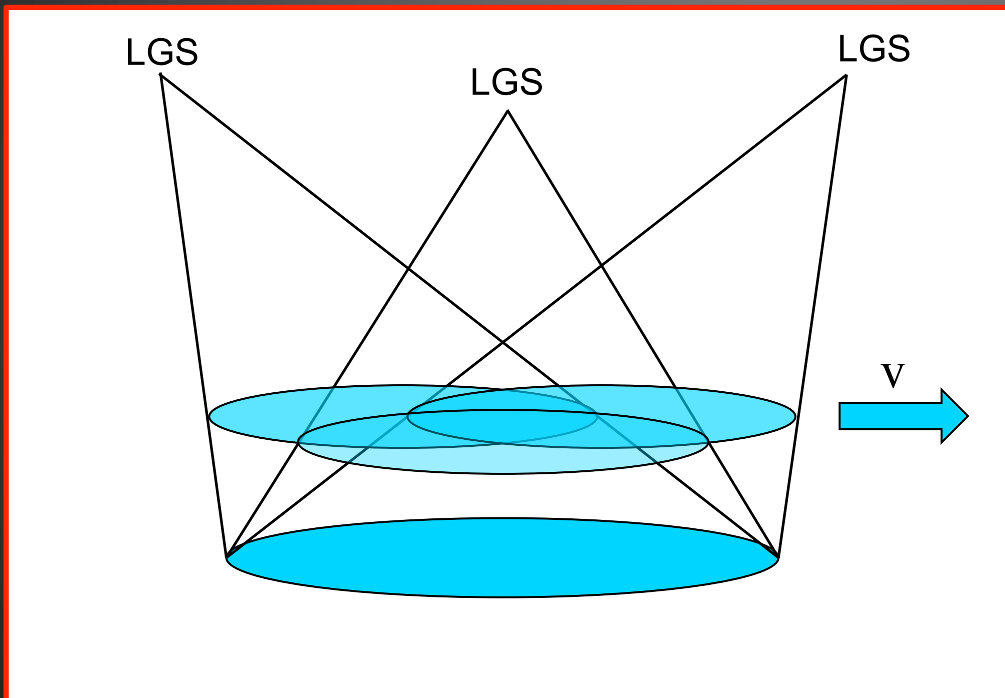
With temporal errors

Removing temporal errors

SOR-like 3.5-meter telescope assumed; S = 19% in i-band with prediction; Temporal wavefront errors = 350 nm RMS without prediction; HST-like orbit

A Tomographic Approach to the Fast-Slewing Problem

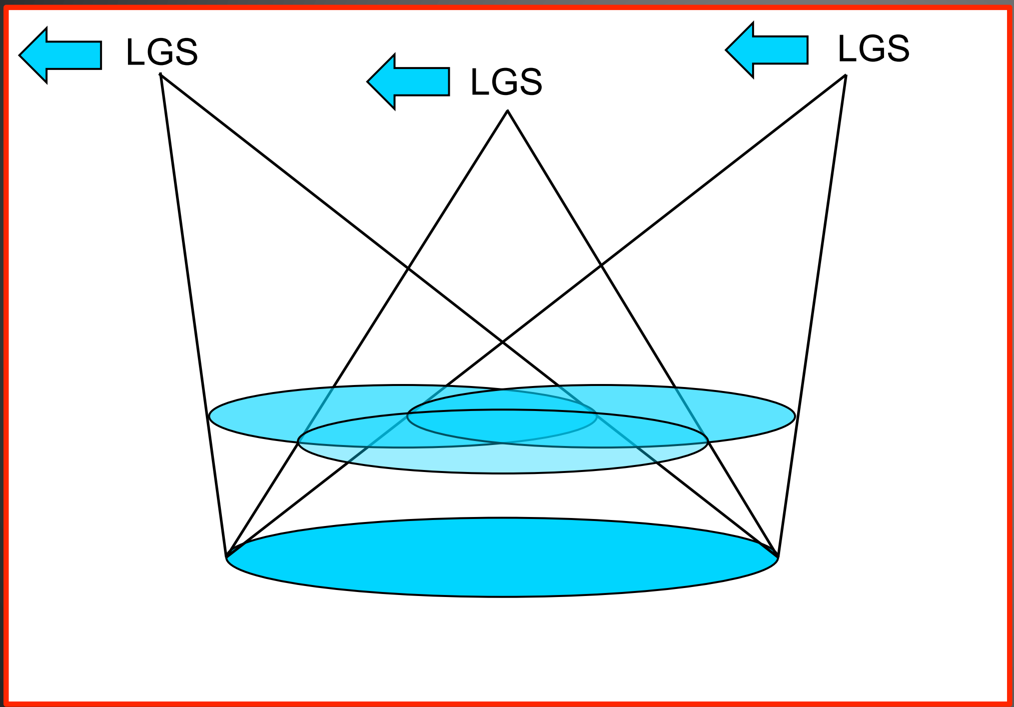
Geometry for Tracking Two Layers



- Example: Two atmospheric layers with static ground layer and upper layer with some velocity

A Tomographic Approach to the Fast-Slewing Problem

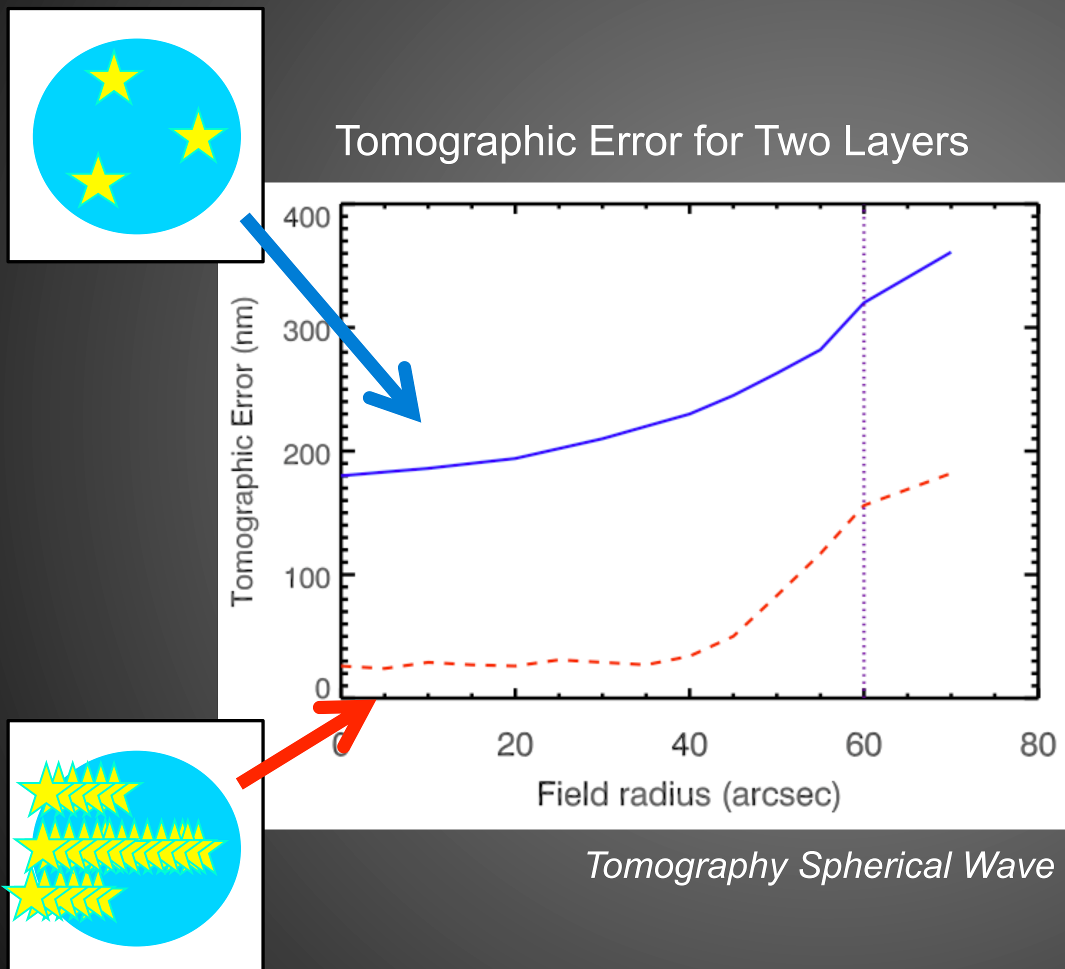
Geometry for Tracking Two Layers



- Geometrically, this is equivalent to an *LGS slewing* scenario in which the guide stars are tracking across the sky
- The atmospheric phase can be tomographically estimated with essentially zero error

A Tomographic Approach to the Fast-Slewing Problem

Tomographic Error for Two Layers

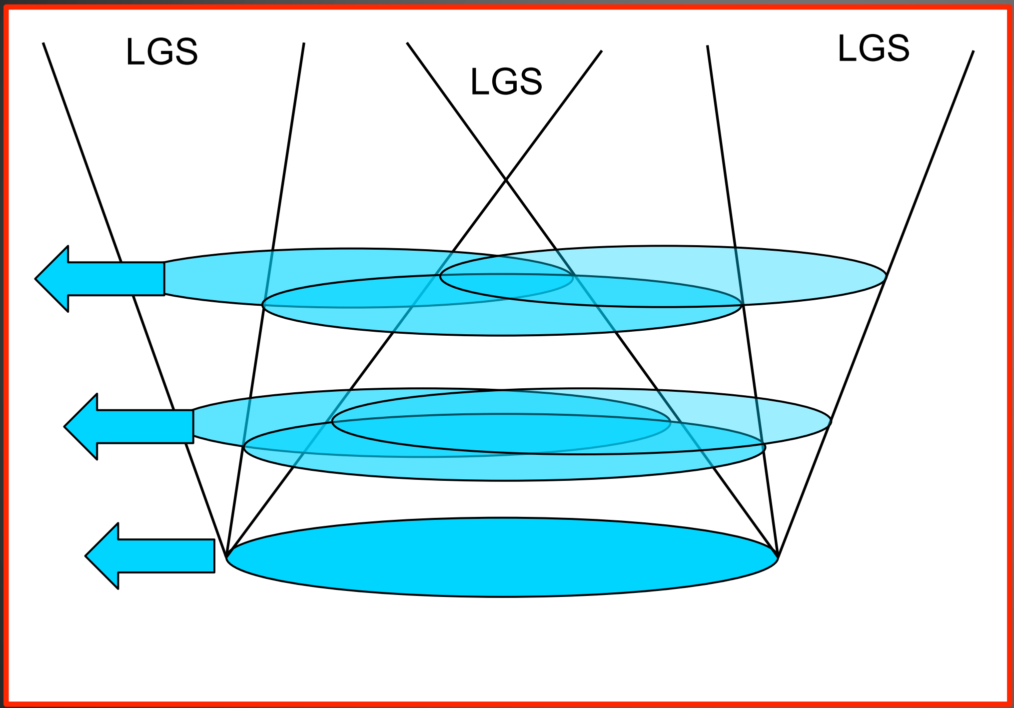


Tomography Spherical Wave

- For any scenario in which the velocity vector is proportional to layer height, the ensemble of previous iterations can be analyzed tomographically, approximating a dense sampling of guide stars.
- This should be generalizable to cases in which layer height is not proportional to velocity.

Simulation Design

Three-Layer Atmosphere



We simulate an 3.5-m telescope with tomography:

- 3 LGSs over 120” diameter
- 3-layer Taylor frozen-flow atmospheric model assumed at 0, 5, 10 km (55%, 30%, 15%)
- Wind velocities randomized, 0-15 m/s
- 200 realizations of 1 second length, 1 kHz operation
- To isolate the effect of prediction on tomographic error, we add *no WFS noise*

Back-Projection Tomography

Minimum Variance Back-Projection Tomography (Gavel 2004)

$$\mathbf{v}_{k+1} = \mathbf{v}_k + \Delta\mathbf{v}_k$$

$$\Delta\mathbf{v}_k = a\mathbf{C}\mathbf{e}_k$$

$$\mathbf{e}_k = \mathbf{y} - \left(\mathbf{A}\mathbf{P}\mathbf{A}^T + \mathbf{N}\right)\mathbf{v}_k$$

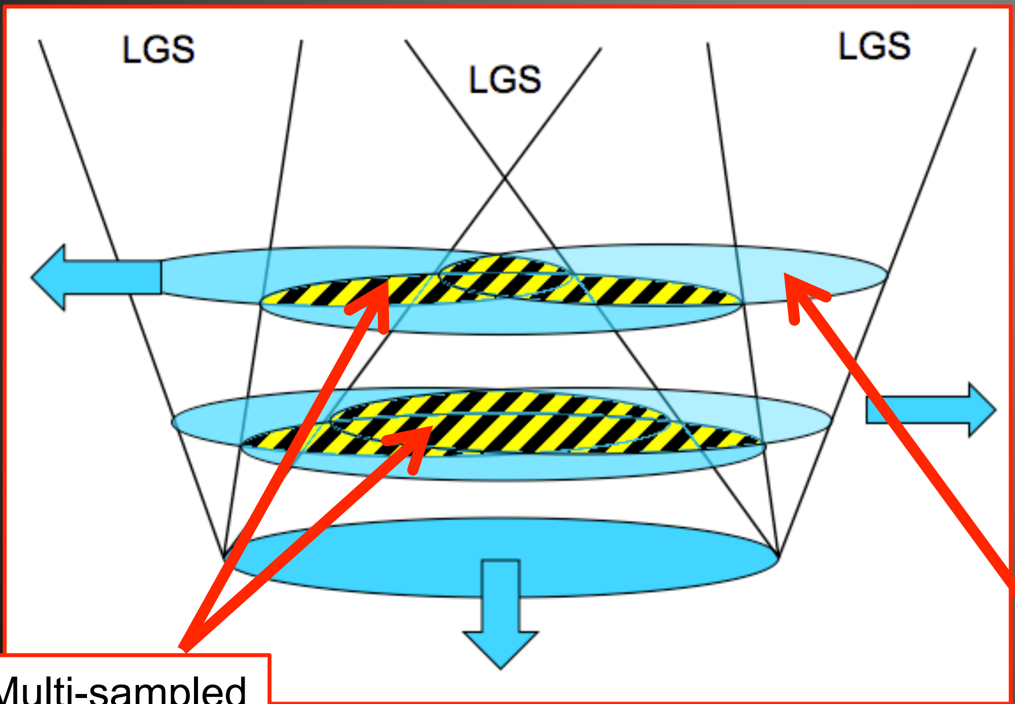
$$\mathbf{x} = \mathbf{P}\mathbf{A}^T\mathbf{v}_\infty$$

$$\mathbf{x} = \mathbf{P}\mathbf{A}^T\left(\mathbf{A}\mathbf{P}\mathbf{A} + \mathbf{N}\right)^{-1}\mathbf{y}$$

- 25 iterations per time step, alternating pre-conditioned conjugate gradient / linear steps

Correction Scheme – Shift & Average Multi-sampled Voxels

$$\Phi'(\mathbf{r},\ t') = \frac{1}{n' - n_0 + 1} \sum_{n=n_0}^{n'} \Phi(\mathbf{r} - c(n' - n)\mathbf{v}, cn)$$



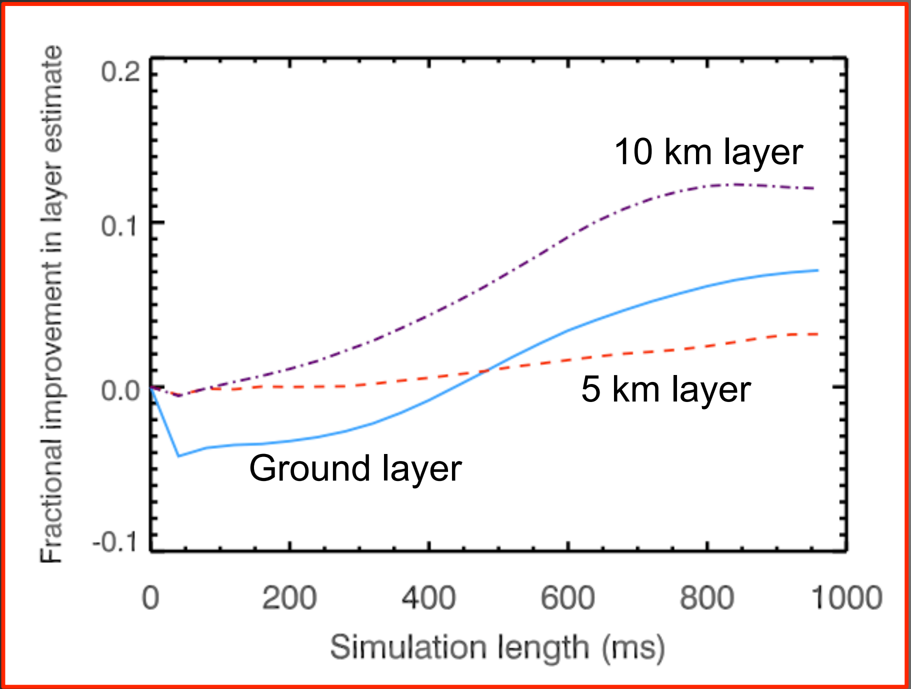
Multi-sampled regions

- For each layer, replace voxels in downwind direction with shifted and averaged voxels from tomographic time history
- Only shift voxels originating in multi-sampled region, where height can be effectively determined
- Wind vectors assumed to be known perfectly

Phase height cannot be constrained in sparsely-sampled regions from tomography alone!

Prediction Improves RMS Errors on Layer Estimates

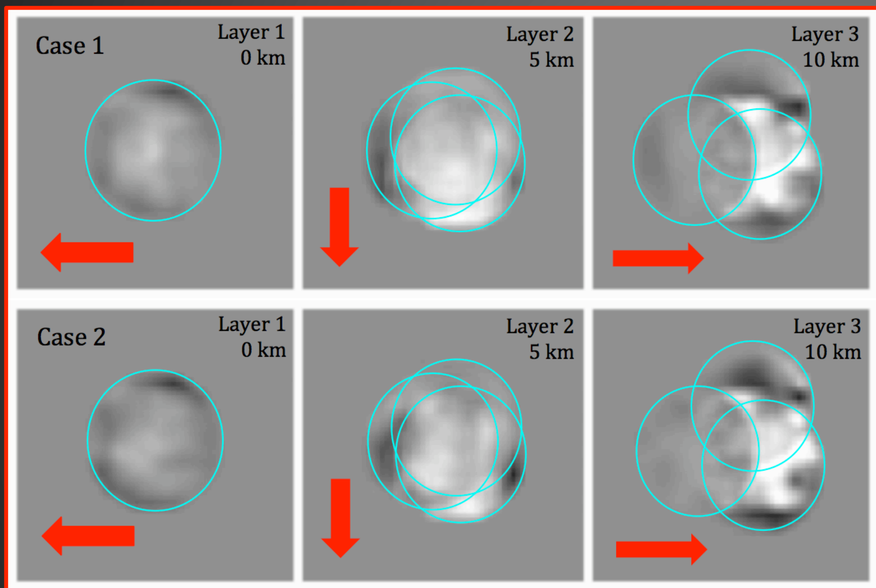
Fractional Improvement in Layer Estimates



- After 1 second, on average, the layer estimates improve 3-13%
- Downwind regions improve 10-30%, especially for high altitude layers

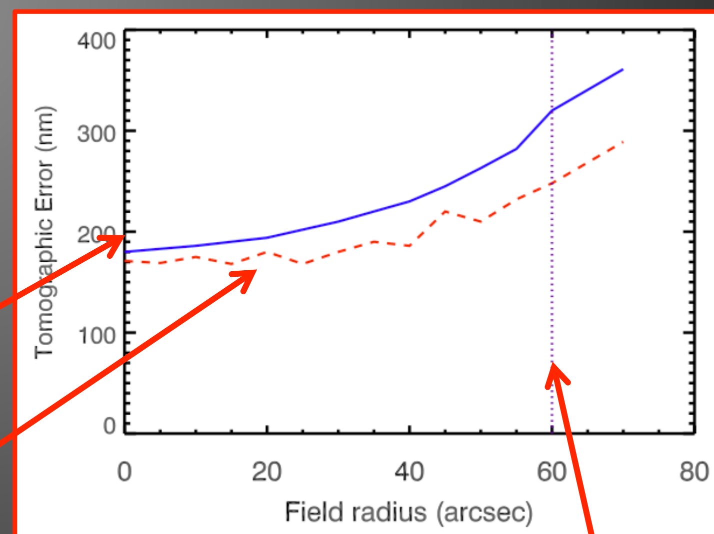
Prediction Improves RMS Errors on Layer Estimates

Maps of Improvement in Layer Estimates



- With downwind layers better determined, the tomographic error improves beyond the radius of the guide stars

Tomographic Error vs. Field Radius



Without shift & average

With shift & average

LGS radius

Conclusions from Simulations

1. Fast-slewing telescopes plagued by temporal errors when tracking LEO objects
2. A tomographic predictive approach could improve wavefront errors and contrast of fast-slewing telescopes
3. In simulation, shifting-and-averaging predictive control provides 3-13% benefits in tomographic wavefront estimation quality at all atmospheric layers (temporal errors not tested)